Germanium Strip Detector Compton Telescope Using Three Dimensional Readout

Eric A. Wulf, W. Neil Johnson, *Member, IEEE,* Richard A. Kroeger, *Member, IEEE,*
James D. Kurfess, *Member, IEEE,* and Bernard F. Phlips *Member, IEEE*

***Abstract*— Compton telescopes using two germanium strip detectors with depth resolution have been demonstrated at the Naval Research Laboratory. Depth resolution allows interactions to be located to less than 1 mm, down from the detector thickness (≈1 cm) with no depth resolution. Depth resolution is shown to improve the imaging resolution of the telescope substantially. Compton images and reconstructed energy spectra are examined using events that interact two or three times with and without full energy losses.**

***Index Terms*— Compton Telescope, Compton Scattering, Semiconductor Detector**

I. Introduction

VARIOUS applications, including astrophysics and locating fissile materials, require the ability to determine the energy of incident gamma rays and image the gamma ray source. The energy of a gamma ray can be determined with a variety of detectors from a scintillator to a semiconductor with varying sensitivity and energy resolution. Determining the location and energy of a gamma ray source can be done with a multitude of techniques for lower gamma ray energies such as a collimator, coded aperture, or Compton telescope with a position sensitive detector. As the gamma ray's energy increases, more material is required to stop it and produce an image. An extension of the Compton technique for imaging that does not require the gamma ray to be completely absorbed in the instrument was explored in [1] and expands the abilities and sensitivity of a Compton telescope.

A. Compton Telescopes

A Compton telescope, such as COMPTEL [2] on NASA's Gamma Ray Observatory, has to stop the gamma ray completely to get the correct direction cosine of the incoming gamma ray. The gamma ray enters the instrument, Compton scatters in the first detector and the Compton-scattered gamma ray is absorbed completely in the second detector. This type of interaction will be called Two-Compton for this paper. Both detectors need to have position and energy resolution in order to reconstruct an image of the gamma ray source using the Compton scattering formula

$$\cos\theta_1 = 1 + m_e c^2 \left(\frac{1}{E} - \frac{1}{E_1}\right), \qquad (1)$$

where θ_1 is the Compton scattering angle of the incident gamma ray, E is the energy of the original gamma ray, and E_1 is the energy of the scattered gamma ray. $E = L_1 + L_2$ where L_1 is the energy deposited at the Compton scattering site and L_2 is the energy deposited when the gamma ray is absorbed. And $E_1 = L_2$ when the gamma ray is stopped completely. From θ_1 and the position of the two interactions, a cone can be drawn and the overlap of the cones from events gives the original source position (see Figure 1).

At higher gamma ray energies, it becomes increasingly difficult to design an instrument capable of stopping the gamma ray completely. Instead, one can use detectors with good position and energy resolution that are thick enough to have the gamma ray Compton scatter twice and then interact one more time. The gamma ray does not have to be fully absorbed at the third interaction site. This will be called Three-Compton for this paper. The positions of these three interaction sites determine the second Compton scattering angle, θ_2. This angle and the energy deposited at the first and second sites, L_1 and L_2 respectively, yield the original gamma ray energy, E, [1]

$$E = L_1 + \frac{L_2}{2} + \frac{1}{2}\sqrt{L_2^2 + \frac{4 m_e c^2 L_2}{1-\cos\theta_2}}. \qquad (2)$$

One can then use Equation 1 with the calculated initial energy and $E_1 = E - L_1$ to determine the first Compton scattering angle. Knowing the original gamma ray energy and Compton scattering angle allows for imaging using the same intersecting ring method used in a traditional Compton telescope (see Figure 1).

It is obvious from Equation 2 that the $\frac{1}{1-\cos\theta_2}$ term is the dominant term for small angles and determination of θ_2 needs to be as accurate as possible. The Compton scattering cross section for high energy gamma rays is dominated by small angle scattering, so good three dimensional position resolution is important to determine θ_2. Thin detectors could be used so

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E. A. Wulf is a National Research Council–Naval Research Laboratory Research Associate in Washington, DC 20375 USA (telephone: 202-404-1475, e-mail: wulf@nrl.navy.mil).
W. N. Johnson is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-6817, e-mail: johnson@ssd5.nrl.navy.mil).
R. A. Kroeger is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-7878, e-mail: kroeger@ssd5.nrl.navy.mil).
J. D. Kurfess is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-3182, e-mail: kurfess@ssd5.nrl.navy.mil).
B. F. Phlips is with the Naval Research Laboratory, Washington, DC 20375 USA (telephone: 202-767-3572, e-mail: phlips@nrl.navy.mil).

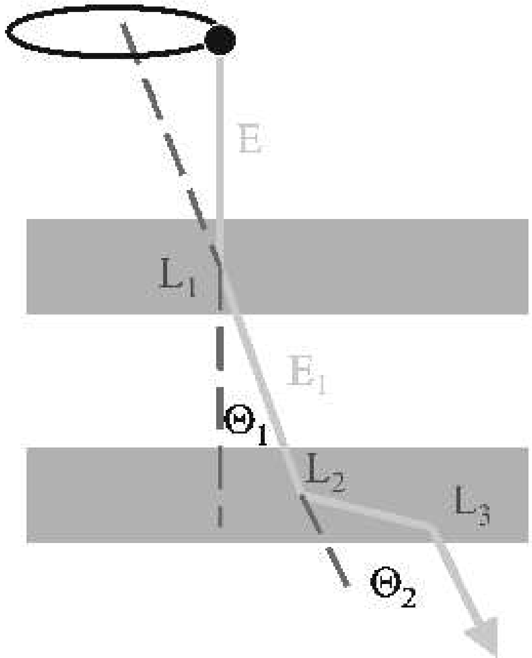


Fig. 1. A cartoon of the experimental setup with 3 interactions (L1, L2, L3) in the two detectors. The source is shown as a large dot on the reconstructed Compton ring. For Two-Compton, imagine the gamma ray stopping at the second interaction point. This experiment only had two detectors so Three-Compton had two interactions in one detector as shown.

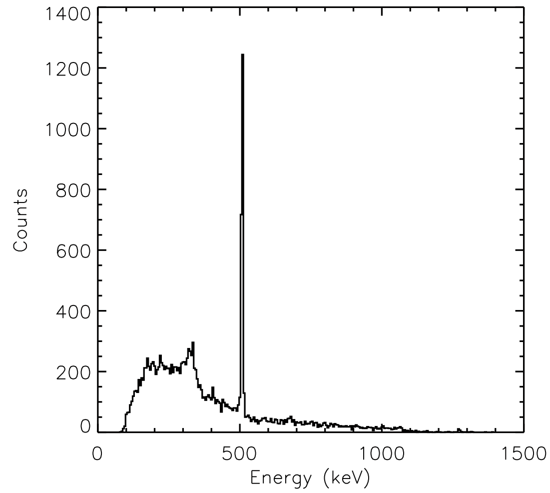


Fig. 2. A spectrum of events that struck both detectors with the total energy deposited in both detectors.

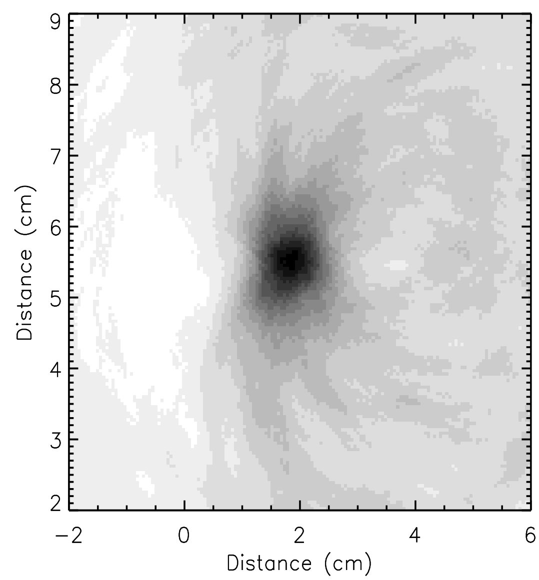


Fig. 3. A Compton ring image of the events from ^{22}Na that interacted once in each detector and whose energy summed to 511 keV, i.e. Two-Compton.

that the interaction depth within each detector need not be measured. Thin detectors require many more channels of electronics to achieve the same amount of detector material one would have with thicker detectors. Thicker detectors require depth resolution or a large separation between detectors to determine the scattering angle as accurately as possible. Unfortunately, a large separation between detectors reduces the efficiency of the instrument. Depth resolution is relatively easy to accomplish and has been recently demonstrated for a germanium strip detector [3] but this requires more complex electronics.

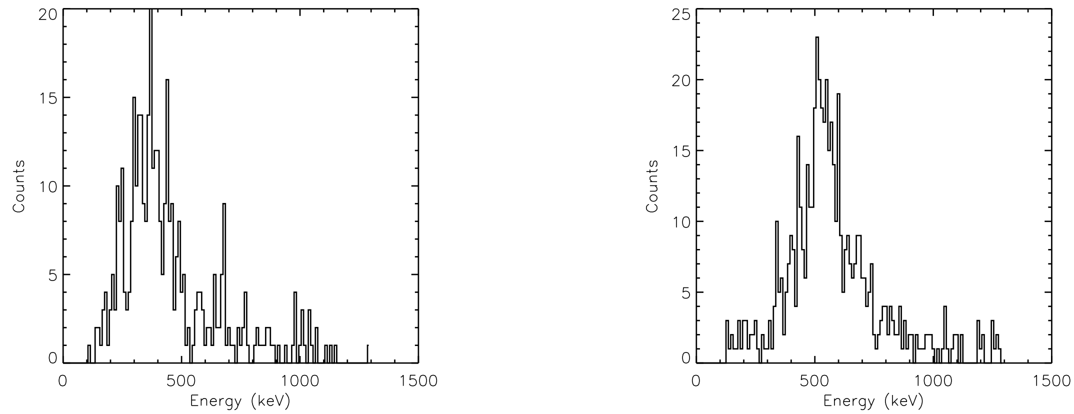
The Compton telescope works well in the Two-Compton mode (two interactions where the gamma ray is stopped) for low energies and Three-Compton mode (three or more interactions where the gamma ray does not have to be stopped) for higher energies. One data set can be taken for both modes and software can be used to select events for each mode. This allows one instrument to span a large energy range.

II. Experimental Setup

The gamma ray imaging laboratory at the Naval Research Laboratory has two germanium strip detectors from Eurisys Mesures in separate cryostats. Three detectors would be a better setup for looking at Three-Compton but that experiment will have to wait for another detector and more electronics. Instead, events that interacted once in one detector and twice in the other were used for Three-Compton (see Figure 1).

One detector is a 25x25 germanium strip detector with 2mm strip pitch and approximately 1 cm in thickness [4]. Boron implants are used on one side and lithium strips on the other. This detector was first used to show three dimensional readout of a detector [3], [5].

Orthogonal strips on the front and rear faces of the crystal allow germanium strip detectors to locate a gamma-ray interaction in two dimensions accurate to the width of the strips. A gamma ray interacts in the crystal and its position is determined by the intersection of the triggered strips on opposite sides of the detector. The depth of the interaction is determined by looking at the timing difference between charge collection of holes on one side of the detector and electrons on the other. The



(a) Original

(b) Reconstructed

Fig. 5. For events that interacted three times, in (a) the original summed spectrum with 511 keV events removed. In (b) is the reconstructed energy spectrum using the Three-Compton technique.

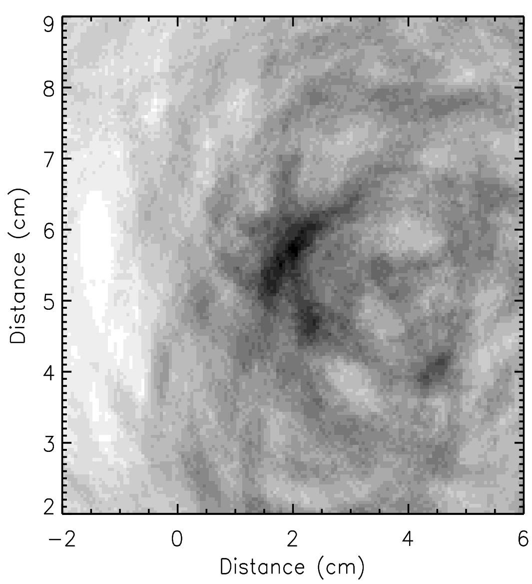


Fig. 4. A Compton ring image of the events from ^{22}Na that interacted once in one detector and twice in the other detector, i.e. Three-Compton.

interaction depth is nearly proportional to this time difference and has been shown to be better than 0.5 mm at 122 keV [3].

The other detector has four identical crystals daisy chained into a 2x2 matrix [6]. Each detector is the same as the single detector.

On the single crystal, 24 of the boron strips and 24 of the lithium strips were instrumented. On the 2x2 matrix, one detector had 16 boron and 16 lithium strips instrumented. The electronics included the NRL NIM timing and shaping electronics [3] and CAMAC Time to Digital Converters (TDCs) and Analog to Digital Converters (ADCs) for all 80 channels.

The detectors were placed with the 2x2 matrix detector closest to the source and the single crystal detector 10.2 cm behind it. To determine the exact orientation of the detectors with respect to each other, a position table scanned a ^{57}Co source collimated to a fan beam across the x and y dimensions of the detectors. The smaller detector was determined to be 0.1 cm to the right of the large detector, when looking from the front of the larger detector, and 1.0 cm lower. A larger position table with a ^{133}Ba source was used to scan, through the table on which the detectors were sitting, the z dimension between the two detectors as well as their depth information. From this it was determined that the crystal in the 2x2 array was 0.9 cm thick and the single crystal was 1.1 cm thick. Depth determination was found to work the same in the 2x2 array detector as it had in the single detector.

III. Results

A. Imaging of a ^{22}Na Source

^{22}Na decays by emitting a β^+ and a 1275 keV gamma ray. The β^+ annihilates and produces back to back 511 keV gamma rays. A 10 μCi source was placed 5.6 cm from the front face of the large detector.

Data were acquired requiring a coincidence between the two detectors. In software, events that struck both detectors once and totaled 511 keV were selected. A spectrum of these events is shown in Figure 2. Because this spectrum was taken in coincidence and summed over both detectors, one will notice the prominent 511 keV peak, the diminished Compton edge, and lack of a 1275 keV peak. Taking the events that summed to 511 keV and drawing Compton rings at a plane 5.6 cm from the front face of the first detector yielded the ring image shown in Figure 3. The Full Width Half Maximum (FWHM) of the ring image point spread function is 1.1 cm for this ^{22}Na source that is 0.5 cm in diameter. Using an energy resolution of 2 keV, a position uncertainty of 2 mm, and the average scattering angle of 60°, one gets an expected width of 0.8 cm. The large average scattering angle and the difference between the measured and expected widths is due in part to the geometry of the system and to Doppler broadening which affects energy resolution as discussed in [7]. The calculated resolution of a Compton telescope made from germanium detectors with infinitely small strips at this energy is about 0.06 cm [8].

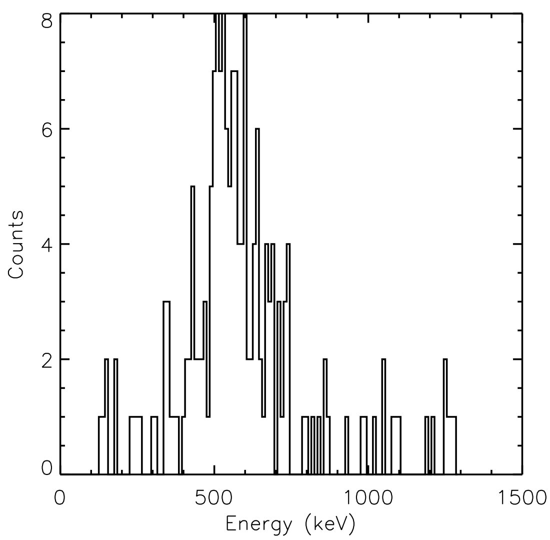


Fig. 6. A reconstructed energy spectrum of Three-Compton events where the path length between interactions had to be greater than 1 cm.

Selecting events that interacted in one detector once and the other twice yields events for Three-Compton. There are nearly 2.7 times more Two-Compton events than Three-Compton events. This number does not truly represent the ratio between Two-Compton and Three-Compton events because it is difficult to determine if the events selected for Two-Compton and Three-Compton are real or background events. For the Three-Compton events, summing the energy deposited in each detector shows that there are events that sum to 511 keV. Taking the events whose energy sum to less than 511 keV, i.e. those gamma rays that were not stopped completely in the instrument, and producing a Three-Compton image shows a point at the same position as the Two-Compton image. The Three-Compton events that sum to 511 keV, gamma rays that were stopped completely, produce an image at the same point. Finally, analyzing the events that had total deposited energy greater than 511 keV, presumably from the 1275 keV gamma ray or a 1275 keV and 511 keV gamma ray in coincidence, also produced an image at the same point. All the Three-Compton events imaged together produces the image shown in Figure 4. This proves that the Three-Compton technique can image at two different energies to the same point as that produced by the standard Two-Compton technique and that this works whether or not the gamma ray is stopped completely by the detectors.

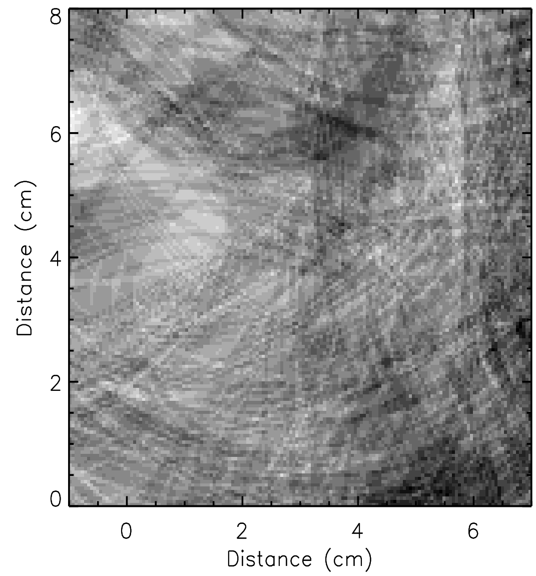


Fig. 7. A reconstructed image of Three-Compton events from ^{22}Na with their depth information suppressed.

Ordering the three interactions that make up a Three-Compton event needs to be done properly in order to get a reconstructed image and energy spectrum. Kroeger *et al.* [7] explored an algorithm to select the correct order of interactions based on Monte Carlo simulations. The algorithm took the six different orderings and calculated a probability based on Compton scattering cross section and attenuation of the gamma ray traveling through the detector,

$$p_{tot} = \sigma_1 \sigma_2 e^{-r_1/t_1} e^{-r2/t_2}, \tag{3}$$

where p_{tot} is the total probability, σ_1 and σ_2 are the Klein-Nishina calculated cross sections for the first and second interactions, r_1 and r_2 are the distances that the scattered gamma rays traveled in the germanium, and t_1 and t_2 are the attenuation lengths in germanium for the appropriate gamma ray energies. The first interaction was assumed to be in the detector closest to the source and the case where the gamma ray interacted in the first detector, then the second detector and then back to the first was assumed to have zero probability. Events that were non-physical, based on the calculated Compton scattering angle, were not considered.

This ordering algorithm works at 511 keV as shown by a reconstructed image with a point at the correct location in Figure 4. The blurring of this image could be due to a number of factors. Ordering the gamma rays is a more difficult task below 1 MeV as was shown in [7]. 511 keV is a particularly bad energy for reconstruction because at least two candidate sequences have nearly equal probabilities over a wide range of scatter angles. Another factor that contributes to the blurring of the image could be misalignments in the system. The scanning of the instrument with the radioactive source would not have shown rotations of the detectors with respect to each other.

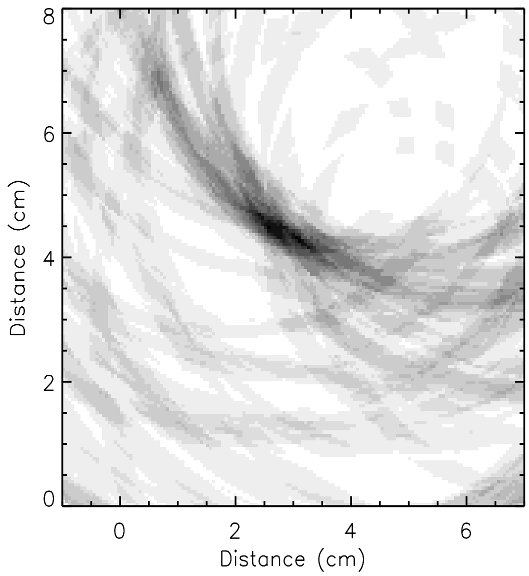


Fig. 8. The Two-Compton image for ^{60}Co is shown. The image is smeared due to low statistics due to the fact that there 30 times more Three-Compton than Two-Compton events. One can see the preferential scattering angle due to the instrument geometry.

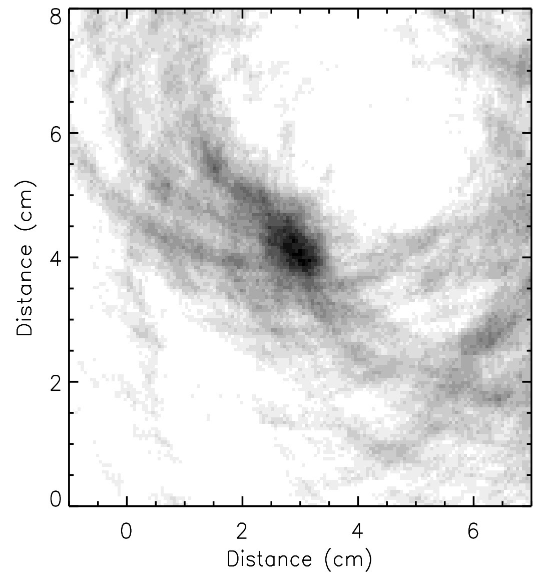


Fig. 9. The Compton ring image from the Three-Compton technique for ^{60}Co. The 1173 and 1333 keV energy lines image to the same point.

Looking at energy reconstruction, one can see the Three-Compton technique can reconstruct the original gamma ray energy. A spectrum of Three-Compton events that do not sum to 511 keV is shown in Figure 5(a) and after reconstruction using Equation 2 in Figure 5(b). Even without a peak at the photopeak energy in the original events the Three-Compton method produces a peak at 511 keV with a high energy tail. A number of the events did not reconstruct to the proper energy probably due to getting the order of interactions wrong and because some events were not originally from 511 keV gamma rays. The high energy tail on the 511 keV peak was also seen in Monte Carlo simulations of lower energy gamma rays and is due to misordered events [7]. Another issue is that the path length between events in the same detector is often 5 mm or less. Requiring that the path length be 1 cm or more reduces the statistics but also improves the reconstructed energy spectrum as can be seen in Figure 6. The longer path length allows the Compton scattering angle to be determined more accurately and should be more helpful at higher energies. This requirement demonstrates a situation similar to a real instrument where the multiple detectors are separated by more than 1 cm. In fact, for a 511 keV instrument with multiple germanium detectors one should be able to attain energy resolution on the order of 30 keV FWHM [7].

For this experimental configuration, depth information is important for Three-Compton imaging but not as important for Two-Compton. This is due to the large dependence on position information in the Three-Compton formula (Equation 2), particularly for forward scattering. Eliminating the depth information smears and shifts the Two-Compton ring image slightly but the image shows no reconstructed point for Three-Compton, see Figure 7.

B. *Imaging of a ^{60}Co Source*

^{60}Co decays by emitting 1173 and 1333 keV gamma rays. A 10 μCi source was placed 5.6 cm from the front of the 2x2 array detector. Choosing Three-Compton events yielded 16 times more events than for Two-Compton at these energies. In fact, making a traditional Two-Compton image of the ^{60}Co yielded an image with a large smear rather than a well defined point due to low statistics (see Figure 8). The Three-Compton image on the other hand yielded a well defined point that was at the same position whether events came from the 1173 or 1333 keV line (see Figure 9). This helps to illustrate the usefulness of the Three-Compton technique for gamma rays that would otherwise be difficult to stop completely.

Reconstructing the energy spectrum for these energies is more difficult with this geometry. Only 2% of the Three-Compton events stopped the gamma ray completely in the instrument so any peak must be due to correct reconstruction. Reconstructing the energy spectrum of all Three-Compton events collected shows almost no peaks at 1173 and 1333 keV. However, when events are selected that traveled at least 1 cm between interactions, the reconstructed spectrum (see Figure 10) shows a peak at both 1173 keV and 1333 keV. This is due to the large fraction of events with small separation, and therefore poor resolution of the critical angle, θ_2, in Equation 2. The geometry of the system with only two detectors is far from ideal but does demonstrate the power of this technique.

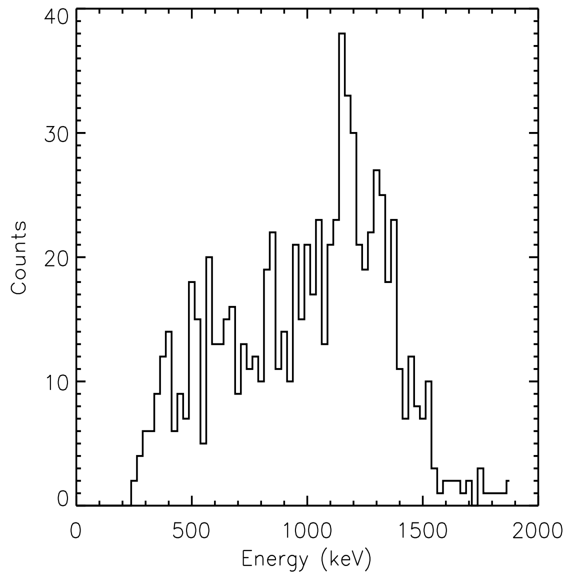


Fig. 10. A reconstructed energy spectrum of Three-Compton events from ^{60}Co where the interactions are separated by at least 1 cm.

IV. Conclusion

The Three-Compton technique is able to produce images that are comparable to those of the traditional Two-Compton method especially at energies over 1 MeV. The Two-Compton and Three-Compton methods can be used to complement each other as their efficiencies change for different energies and instrument configurations. The ability to reconstruct the gamma ray's position and energy without stopping it completely will enable the construction of Compton telescopes for high energy gamma rays that are smaller than if they had to stop the gamma ray.

The experimental setup was not ideal and did not maximize the efficiency of the system but was able to demonstrate a working Compton telescope. The small distance between events reduced the instrument's ability to reconstruct the Compton rings and original gamma ray energy. Instrumenting three working detectors and having the detectors inside of one cryostat where their orientations are known would improve the abilities of the telescope.

The ordering algorithm explored by Kroeger *et al.* [7] for Monte Carlo simulations works well for a real instrument. Further explorations of ordering algorithms need to be pursued to help maximize the utility and resolution of the system. Monte Carlo simulations using Geant4 of a Three-Compton telescope are underway to give a data set where the correct order is known. A maximum likelihood method of imaging also needs to be implemented to help clear up the artifacts from using raw ring images.

Demonstrating a Compton telescope constructed from silicon strip detectors will allow exploration of the effects of Doppler broadening because Doppler broadening reduces with decreasing atomic number. The FWHM of the reconstructed Three-Compton energy spectrum in silicon detectors is simulated to be about 15 keV at 511 keV [7]. Making a large area instrument with many layers of detectors should allow efficiencies on the order of 17% for Three-Compton interactions in germanium detectors and 5% for Two-Compton for 1 MeV incident gamma rays [7].

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